N91-30245

Temperature Coefficients and Radiation Induced DLTS Spectra of MOCVD Grown n^+p InP Solar Cells

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Abstract

The effects of temperature and radiation on n^+p InP solar cells and mesa diodes grown by metallorganic chemical vapor deposition (MOCVD) have been studied. Prior to irradiation, the performance of several solar cells as a function of temperature from 90 to 400 K was measured and temperature coefficients of the photovoltaic parameters will be presented. The solar cells and diodes were then electron and proton irradiated, and the radiation induced defects (RID) were characterized by Deep Level Transient Spectroscopy (DLTS) and by I-V measurements on the cells thus providing the most direct evidence available of a relationship between the changes in the solar cell performance with changes in the H4 defect concentration. In contrast to previous work (Yamaguchi, 1990), the DLTS spectra induced by the proton and the electron irradiations were essentially the same. Also, the relative number of defects found as a result of the electron and proton irradiation is shown to be proportional to the calculated non-ionizing energy loss (NIEL) in InP, indicating that the same defect structure was produced in both cases, in agreement with the DLTS results. Minority carrier injection annealing experiments were then performed on the irradiated diodes at 200 K. The results showed that in both the electron and proton irradiated samples, the injection caused a substantial reduction in the major RID labeled H4. However, the H4 defect could not be completely eliminated but instead displayed a non-zero, asymptotic limiting concentration. Furthermore, this residual defect concentration was about 50% greater in the proton than in the electron irradiated diodes. In contrast, thermal annealing of the diodes at 375 K showed no residual defect concentration.

Introduction

Due to the superior radiation resistance of InP over Si and GaAs (Yamamoto, 1984 and Weinberg, 1985) and its ability to anneal radiation damage at relatively low temperatures and by minority carrier injection (McKeever, 1991 and Walters, 1991), InP has been considered as a space solar cell material since 1984. Progress in developing these cells has been extremely rapid resulting in the production of 4 cm^2 cells of over 19% efficiency (air mass zero (AM0), 25 °C) in the U.S. in 1989 (manufactured by the Spire Corp. under an NRL contract) and the launch of the MUSES-A Lunar Orbiter spacecraft powered by 1300 InP solar cells in 1990 (Yamaguchi, 1990). Despite this rapid device development, the effects of temperature and irradiation on InP devices has not been fully studied. The only temperature effects studies are those of Weinberg et al. which produced results which either varied substantially among different InP cells (Weinberg, 1987) or covered only a limited temperature range (Weinberg, 1990). Three proton irradiation studies have been published (Weinberg, 1986; Takamoto, 1990; and Yamaguchi, 1990). However, since they used room temperature I-V measurements to characterize the irradiated solar cells and InP readily anneals under minority carrier injection, the interpretation of their results is not clear. Furthermore, the recent DLTS study of proton irradiated InP diodes (Yamaguchi, 1990) showed that protons in the range 2 to 7 MeV produced a DLTS spectrum significantly different than that produced by 1 MeV electrons which, from a kinematic viewpoint, is quite unexpected.

In this study, high efficiency MOCVD InP solar cells (≈18%) were illuminated with simulated solar light (AM0) in a DLTS cryostat. The cell temperature was varied over the range of 400 to 90 K, I-V curves were measured, and temperature coefficients for the photovoltaic parameters were determined. There was little variation in the measured values over all the cells. The solar cells were then irradiated with 3 MeV protons and 1 MeV electrons along with diodes of identical structure. The RID were characterized by DLTS measurements on both the cells and diodes, and the solar cell degradation was characterized by I-V measurements made at 90 K. At this low temperature, the AM0, 1 sun I-V measurement did not induce minority carrier injection annealing. It is shown that 3 MeV proton irradiation of MOCVD InP produces a DLTS spectrum essentially identical to that of 1 MeV electron irradiated InP. Also, the results show, for the first time, the actual DLTS spectrum corresponding to the changes in the performance of MOCVD grown InP solar cells.

Experimental Notes

Figures 1a and b show a schematic drawing of the solar cells and diodes, respectively. Both device types were grown by metallorganic chemical vapor deposition (MOCVD) with identical internal structure. The 3 μm thick base p region was Zn doped to a level of 3 $x10^{16}$ cm^{-3}, and the n^+ region doping level was > 10^{18} cm^{-3}. The inset of figure 2 is a typical set of pre-irradiation photovoltaic parameters measured at room temperature.

The cells were illuminated through a sapphire window in the DLTS cryostat by an Oriel 1000 W, Xe arc lamp solar simulator at 1 sun intensity, air mass zero (AM0). The simulator intensity was calibrated by standard cells and was constant to within 0.15 % during the measurements.

DLTS measurements were made using a Bio-Rad DL 4600 spectrometer. For all DLTS scans, a -2 v reverse bias was used which defined a ≈ 0.5 μm depletion region. In the solar cells, hole traps were detected with a 200 ms, 0 v fill pulse while electron traps were detected with a 50 ms, 1.5 v fill pulse. These pulses saturated the DLTS peak heights. In the diodes, the same voltage pulses were used with a 1 ms pulse width (unless stated otherwise).

The 3-MeV proton irradiation was performed at room temperature, in the dark, with a 60 nA current using the Pelletron Accelerator at the Naval Research Laboratory. A Faraday cup was used for dosimetry. The 1 MeV electron irradiation was performed using the Van de Graaff accelerator at NASA Goddard with a current density of 0.2 $\mu A/cm^2$. A Faraday cup and calibrated radiochromatic films were used for dosimetry.

Results

The first results of this study are the temperature coefficients of the photovoltaic parameters of the solar cells. Prior to irradiation, the solar cell temperature was changed from 90 to 400 K in 25 K steps and the I-V curve was measured at each step (figure 2). From these curves, the value of the short circuit current (Isc), open circuit voltage (Voc), maximum power (Pmax), fill factor (FF), and efficiency (Eff) were determined and plotted vs. temperature (figures 3 (a)and(b)). For each cell measured, the data for each parameter over the entire temperature range could be fit to a straight line to within <5 %. Therefore, the temperature coefficient was determined as the slope of the best fit straight line. The coefficients were then averaged over all of the cells to give the final values (table 1). The errors in table 1 are the standard deviations of the averages over the different cells. The relatively large error for the FF may be due to loose top metalization contacts on some of the cells which introduced a temperature dependent series resistance into the cell contacts.

The solar cells and mesa diodes were then irradiated with 3 MeV protons up to a fluence of 5 $\times 10^{12}$ cm^{-2}. Several other mesa diodes were irradiated with 1 MeV electrons up to a fluence of 3 $\times 10^{15}$ cm^{-2}. Immediately after irradiation, the DLTS hole trap spectrum was measured in each set of devices. The minority carrier traps were not measured until after the radiation damage was characterized to avoid minority carrier injection annealing effects. The DLTS spectra measured in the proton irradiated solar cells was similar to that measured in the proton irradiated diodes (figure 4) (for an example of the spectrum measured in the diodes see Walters, 1991). The spectrum measured in the electron irradiated diodes is shown in figure 5. Comparison of figures 4 and 5 shows that all the defects seen following electron irradiation are seen in the proton irradiated samples. The defect labeled HP1 in the proton irradiated spectrum is detected in electron irradiated samples at higher fluences than used here, and EC was seen in the electron irradiated samples after an annealing stage (private communication from S. Messenger). The measured parameters of the defects in figure 4 (table 2) match well with values measured in several other studies (McKeever, 1991; Yamaguchi, 1988; and Sibille 1982).

As expected, the defect introduction rate for 3 MeV protons was substantially higher than for 1 MeV electrons- the measured ratio is ≈760. For predictive purposes, it is necessary to determine whether the defect introduction rate is proportional to the calculated NIEL value. The NIEL calculation estimates the average number of vacancy-interstitial pairs initially produced by the irradiation (Burke, 1986). For the energies involved here, the cross sections for both 3 MeV protons and 1 MeV electrons are essentially Rutherford-like and the calculation is relatively straight forward. Similar calculations of the NIEL as function of incident electron and proton energy for Si and GaAs have been discussed in detail previously (Summers, 1988 and references therein). Briefly, the calculation involves a product of the cross section for interaction and the recoil energy, corrected for Lindhard energy partition (Lindhard, 1963). The calculation shows that the ratio of the NIEL for 3 MeV protons to 1 MeV electrons in InP is ≈740. The agreement of this calculated ratio with the measured ratio of introduction rates indicates that the H4 defect introduction rate is directly proportional to the number of defects initially produced by the irradiation. This is a important result for predicting radiation induced degradation in InP devices in general.

To further characterize the radiation damage, I-V measurements were made at 90 K on an irradiated cell (figure 6). The measurement shows that the irradiation reduced the Isc by 54%, the Voc by 2.5%, and the Pmax and Eff by 71%. A DLTS spectrum taken immediately following this measurement was identical to that of figure 4 which insures that no minority carrier injection annealing was induced by the illumination. This is the first data which clearly shows the defect spectrum corresponding to the radiation induced degradation of the solar cell performance before injection annealing.

After the radiation induced defects were measured, minority carrier injection annealing studies were performed on the diodes. Figure 7 shows the results of injecting an electron irradiated InP mesa diode with 6.4 mA/cm^2 and a proton irradiated InP mesa diode with 30 mA/cm^2 at 200 K. While the sensitivity of the H4 defect to injection is well known (Ando, 1986; McKeever, 1991; and Walters, 1991), figure 7 shows that not all of the H4 defect concentration will anneal under injection at this temperature. In both cases, the H4 defect concentration approaches a non-zero, limiting value, and this residual defect concentration seems to be about 50% larger in the proton irradiated samples than in the electron irradiated samples. However, also depicted in figure 7 is the results of isothermal annealing at 375 K of a proton irradiated diode. Over 5 hours of annealing, this data shows a first order annealing process. The same activation energy was measured for the H4 defect by DLTS before and after the injection annealing. The cause of this annealing behavior and its effect on the long term solar cell performance in a space environment is uncertain and still under investigation.

Discussion

When measuring the properties of a material, the main concern is the consistency of the measurement from one sample to the next. The uncertainties of the temperature coefficients presented in table 1 indicate that this is a reliable data set describing the temperature variation of InP solar cell performance over a large temperature range. The magnitude of the coefficients indicate the necessity of considering the operating temperature of the cell when predicting its performance. It is concluded that, given a single measurement at room temperature on a good quality MOCVD n^+p InP cell, these coefficients enable an accurate estimate of the cell performance through the 90-400 K temperature range and will be useful in any modeling study.

To completely characterize a solar cell for space fight, the effects of radiation on the cell performance must be well understood. To this end, this study has shown that the defects produced by 1 MeV electron irradiation of MOCVD InP solar cells are the same as those produced by low energy proton irradiation. Also, since the defects were measured in the actual solar cells, the degradation of the solar cell performance has been clearly associated with the introduction of the major RID labeled H4. Until now, this conclusion was based on circumstantial evidence measured on different samples. Furthermore, this study has suggested a linear dependence of the defect introduction rate on the calculated NIEL value for a given incident particle. Since the NIEL value can be relatively easily calculated for a any given incident particle spectrum, this result would allow the calculation of the damage rate due to an entire spectrum of irradiating particles from a measurement of the damage due to irradiation at a single energy.

Finally, this study has shown that, at 200 K, minority carrier injection annealing is unable to completely eliminate the H4 defect, and the residual defect concentration was about 50% larger in the proton than in the electron irradiated samples. It seems that while there is only a single defect level producing the H4 DLTS peak, there is some portion of the H4 defect concentration which is insensitive to the injection annealing. While the reason for this behavior is still uncertain, it does seem to pose a limiting factor on the long term radiation resistance of InP at low temperatures. However, since the thermal annealing behavior at 375 K, which is near the normal operating temperature of a space solar cell, did not show this behavior, it is expected that, under normal space solar cell operating conditions, the combination of minority carrier injection and thermal annealing of the H4 defect will make InP extremely radiation resistant. This conclusion confirms the results of several previous studies (Yamamoto, 1984 and Weinberg, 1985).

Conclusions

This study has shown that MOCVD is capable of consistently producing good quality InP solar cells with Eff > 19% which display excellent radiation resistance due to minority carrier injection and thermal annealing. It has also been shown that universal predictions of InP device performance based on measurements on a small group of test samples can be expected to be quite accurate, and that the degradation of an InP device due to any incident particle spectrum should be predictable from a measurement following a single low energy proton irradiation.

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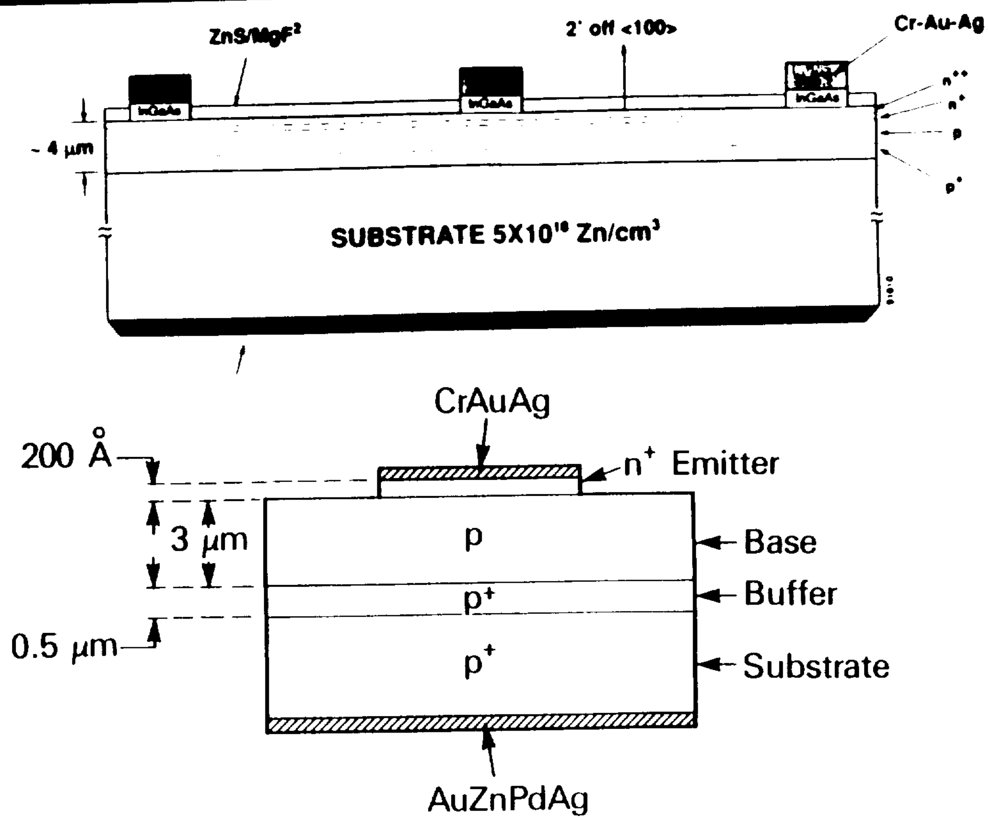
TABLE 1
Temperature coefficients for InP Solar Cells

$\frac{dIsc}{dT}\ \frac{\mu A}{K}$	$-\frac{dVoc}{dT}\ \frac{mV}{K}$	$-\frac{dPmax}{dT}\ \frac{\mu W}{K}$	$-\frac{dFF}{dK}\ \frac{10^{-4}}{K}$	$-\frac{dEff}{dK}\ \frac{10^{-2}\%}{K}$
7.81 ± 0.68	1.939 ± .051	10.45 ± .85	5.3 ± 1.3	3.07±.25

TABLE 2
Parameters of Defects Measured in Irradiated
MOCVD Grown n^+p InP Solar Cells and Diodes by DLTS

	HP1	H2	H3	H4	H5	H7	EA	EB	EC
E_a (eV)	.15	.20	.30	.37	.54	.61	.26	.74	.16
σ_∞ $\times 10^{15}$ cm^{-2}	.048	.011	.66	.14	6.0	5.3	30	500	2.0



(b)

Figure 1. Schematic drawings of the (a) solar cells and (b) mesa diodes

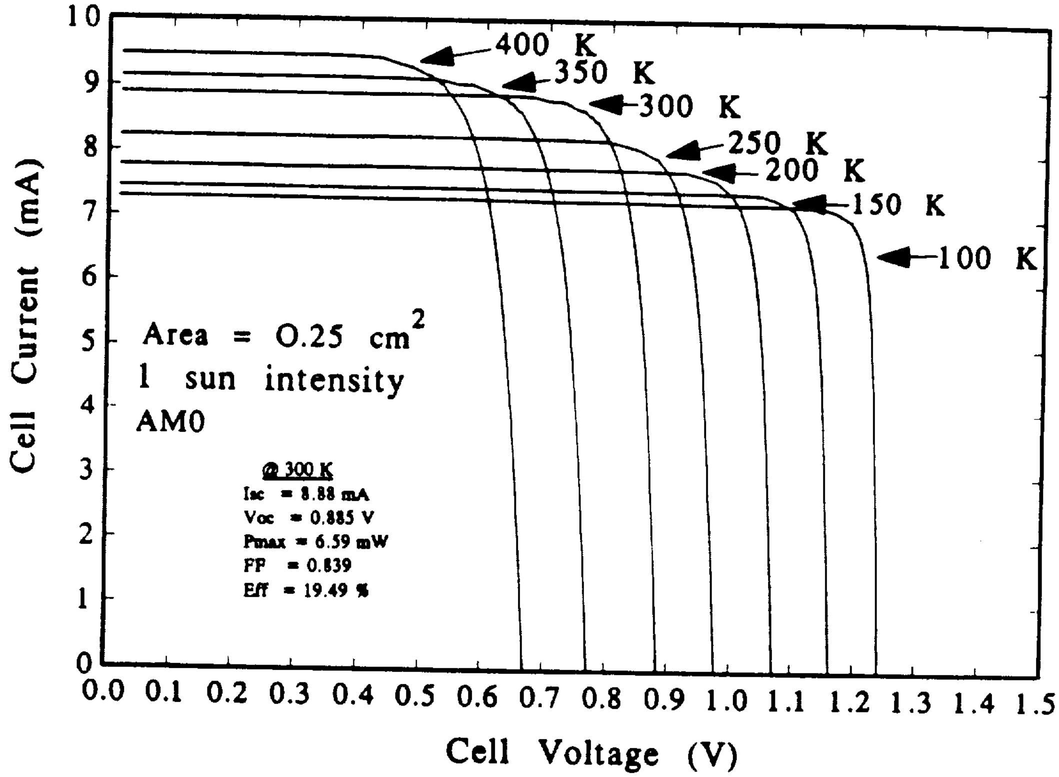


Figure 2. A typical set of I-V curves measured vs. temperature from 400 to 90 K

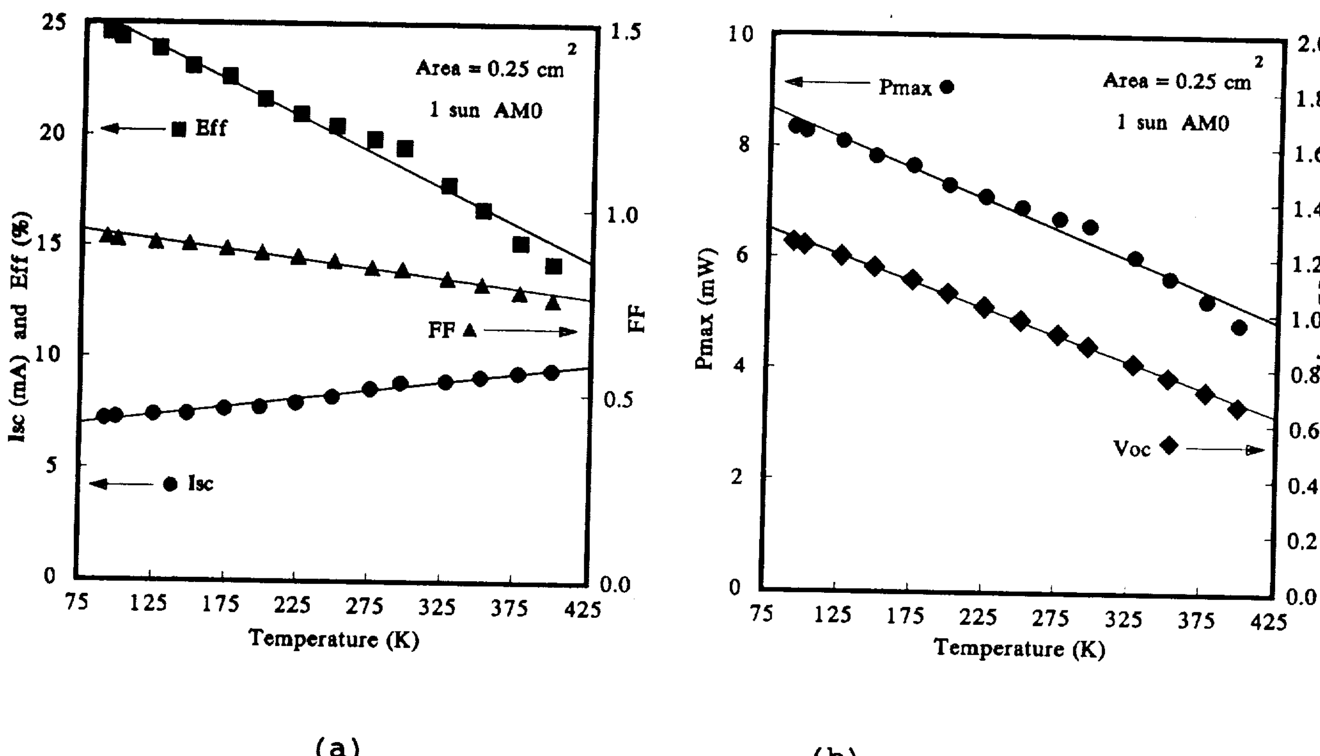


Figure 3. The plots of the photovoltaic parameters gained from the above I-V curves vs. temperature.

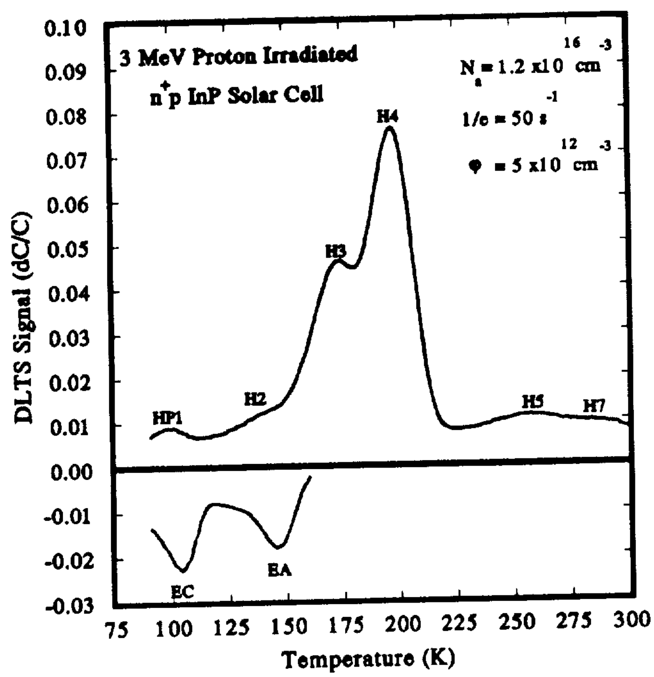


Figure 4. Typical DLTS spectrum of a proton irradiated InP solar cell

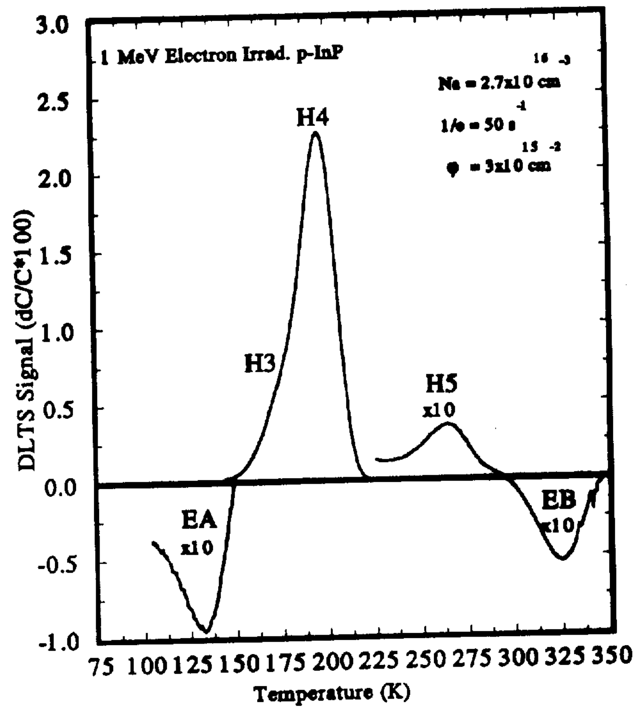


Figure 5. Typical DLTS spectrum of an electron irradiated InP diode.

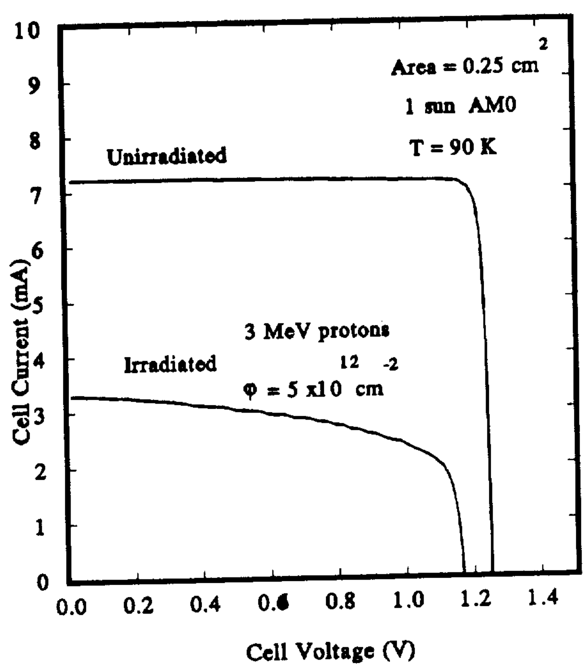


Figure 6. Typical I-V measurements at 90 K before and after proton irradiation

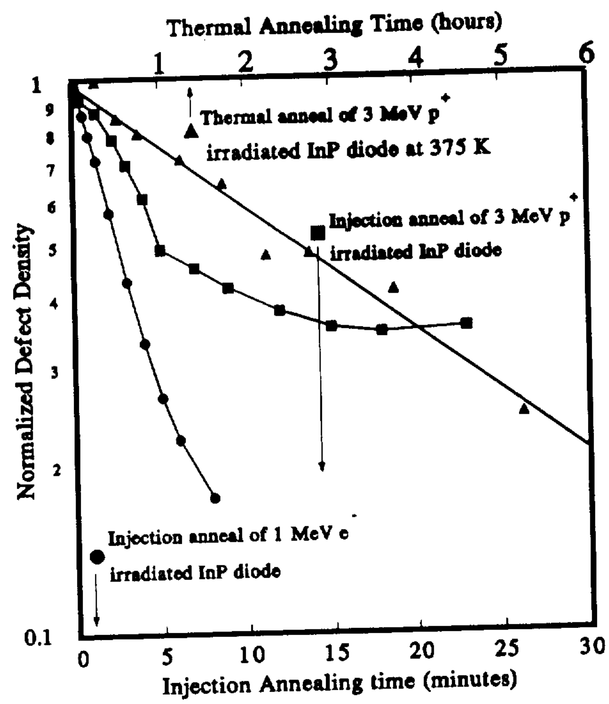


Figure 7. Comparison of the annealing behavior of the H4 defect